STUDY ON NEUTRON – GAMMA PULSE SHAPE DISCRIMINATION ALGORITHMS FOR SCINTILLATION DETECTOR

Phan Van Chuan[a*], **Nguyen Duc Hoa**[b],
Nguyen Dac Chau[c], **Vuong Nu Minh Khue**[d]

[a]*The Faculty of Physics, Dalat University, Lamdong, Vietnam*
[b]*The Faculty of Nuclear Engineering, Dalat University, Lamdong, Vietnam*
[c]*Vietnam Naval Academy, Khanhhoa, Vietnam*
[d]*The Communist Party Office, Dalat University, Lamdong, Vietnam*

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Abstract

The four neutron - gamma pulsed shape discrimination algorithms for the model NE213 scintillation detector by using digital signal processing were developed. In this study, a pulse generator, pulse digitizer and neutron - gamma pulsed shape discrimination algorithms are simulated in Matlab, Simulink software. The results obtained show that the method to rise-time discrimination has a quality factor (Figure-of-Merits: FOM=1.09), pulsed gradient analysis method (FOM = 0.66), charge comparison method (FOM = 2.21), and correlation pattern method (FOM = 1.97). This result is the basis for building systems for measurements of neutron using scintillation detectors.

Keywords: Correlation pattern method; FOM; Neutron-gamma pulse shape discrimination; Simulation of neutron and gamma pulse.

1. INTRODUCTION

The neutron - gamma pulse shape distinguish (PSD) technique is very important in neutron radiation measurements using the scintillation detector. Some of the neutron detectors using liquid organic scintillation like NE213 provide the output pulse which has characteristic to help distinguishable with noisy gamma, which enables the neutron measurements to be more accurate. Besides, by applying the neutron - gamma discrimination technique, it is possible to measure the spectra of neutrons and gamma rays concurrently in a single measurement.

Various neutron - gamma discrimination techniques have been developed, including analog and digital using to discrimination of neutron and gamma-ray events

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[*] Corresponding author: Email: chuanpv@dlu.edu.vn

from scintillation detector, e.g., zero crossing method/constant fraction discriminators (Roush, Wilson & Hornyak,1964; Bayat et al., 2012), charge comparison method (Bayat et al., 2012; Cerny et al., 2004), frequency gradient analysis (Liu et al., 2010), rise time discrimination method, pattern recognition method (Takaku, Oishi & Baba, 2011) etc. However, the studies of neutron - gamma PSD were performed on each separate method that have not compared the effects of neutron - gamma discrimination methods with the same of neutron detector yet.

Recently, a digital signal processing (DSP) technique has grown, which allows implementing the neutron - gamma PSD algorithms of the neutron detection system (Cerny et al., 2004 ; Liu et al., 2010 ; Takaku, Oishi & Baba, 2011 ; Marrone et al., 2002). The DSP Technique is also applied to almost all methods PSD e.g. the zero crossing method and charge comparison method (Liu et al., 2010; Takaku, Oishi & Baba, 2011; Jastaniah & Sellin, 2002). In the neutron - gamma PSD systems using DSP technology, a pulse from detector a pulse would be digitized by the analog to digital converters (ADC) with high speed and data stored in memory in the form of tables. And then, the data of pulse are analyzed with the neutron - gamma PSD method on a computer (Takaku, Oishi & Baba, 2011; Marrone et al., 2002; Jastaniah & Sellin, 2002), or on the board FPGA/DSP (Liu et al., 2010). However, the data sampling take much time and data memory storage.

In the present study, we have developed a simulation model neutron - gamma PSD in DSP which consists of the simulator generator neutron and gamma pulses of the NE213 detector with the parameters (Marrone et al., 2002), the digitized using the behavioral modeling of pipelined ADCs (Barra et al., 2013) to sample the pulse signals and the neutron - gamma PSD for each algorithm. The model is built and simulated in the Matlab Simulink software.

Also, we construct four the neutron - gamma PSD algorithms using digital techniques, including rise time discrimination, pulse gradient analysis, charge comparison method and pattern recognition method. The analysis results of four methods would be the basis for the selection of the neutron - gamma PSD algorithm for building the neutron measurements using the scintillation detector.

2. EXPERIMENT

The schematic view of the simulation neutron - gamma PSD algorithms is shown in Figure 1. It consists of a neutron-gamma pulse generator, an electronic noise generator, an analog to digital (ADC), a filter, and the processing pulse that performs the PSD algorithms. The pulsed neutron-gamma is produced from the block "neutron-gamma pulse generator" that has an amplitude and start time randomly. Each pulse after passing through the sampling will be filtered to reduce the noise, and then the pulses are taken to processing block used to PSD with different algorithms.

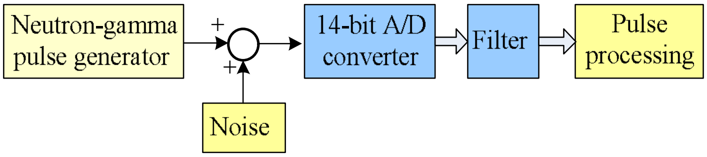

Figure1. The model simulation neutron - gamma PSD algorithms on Matlab Simulink

2.1. Simulate the pulsed neutron-gamma for the NE213 scintillation detector

The mathematical expression of pulses produced from the scintillation detector is referenced from Marrone's model, including 6 parameters (Knoll, 2000; Spieler, 2002) and is given by (1).

$$y(t) = A\left[e^{-\frac{t-t_0}{\tau_1}} - e^{-\frac{t-t_0}{\tau_S}} + \frac{B}{A} e^{-\frac{t-t_0}{\tau_L}} \right] \qquad (1)$$

Where, A and B are the amplitudes of the short (fast) and long (slow) life components at t = 0, respectively, τ_s is the decay time constant for the short life component, τ_L is the decay time constant of the long life component, τ_1 is the time constant of the anode, the preamplifier, connecting cable and input stage of the ADC. The t_0 is the time reference for the start of the signal. In this study, the parameters for the NE213 scintillation detector were presented in Table 1 (Marrone et al., 2002). The data are assumed according to a Gaussian distribution and a standard deviation of 10%.

Table 1. The parameter is used for scintillation NE213 simulation

Parameters	B/A	τ_1 (ns)	τ_S (ns)	τ_L (ns)	t_0 (ns)
Gamma	1.658×10^{-2}	5.578	4.887	34.276	0.31
Neutron	4.151×10^{-2}	5.578	4.887	34.276	0.31

Source: Marrone et al. (2002)

2.2. Simulating electronic noises

2.2.1. Thermionic emission

The typical spontaneous emission rate at room temperature is in the range of $10^2 \div 10^4$ electrons/cm^2.s (Knoll, 2000). In most cases, these pulses originating from one single electron are often of small amplitude.

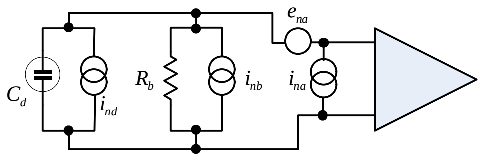

Figure 2. Equivalent circuit for noise analysis

2.2.2. Noise by dark current fluctuations in the photo multiplier tube (PMT)

A small amount of current flows inside of a PMT even when operated in a completely dark state that is called the anode dark current. The fluctuations of dark current generated the noise signals and they have formed Gaussian standard deviation, calculated by the equation (2) (Knoll, 2000).

$$\sigma_Q = \sqrt{6\times10^{18}}\sqrt{U\tau / R} \tag{2}$$

Where, U is the value height voltage, τ is the time constant of the electronic circuit and R is the bias resistor of PMT.

2.2.3. The fluctuation of electrons goes to the anode

The number of electrons to anode fluctuates statistically. The fluctuations are noise white and they are calculated according to the equation (3) (Spieler, 2002).

$$e_{nd}^2 = i_{nd}^2 \frac{1}{(\omega C_D)^2} = 2q_e I_D \frac{1}{(\omega C_D)^2} \tag{3}$$

Where, I_D is the bias current of detector, q_e is the electron charge, $\omega = 2\pi / \tau$ is the cut off frequency of electronic circuit, C_D is the capacitance of the detector.

2.2.4. Thermal noise in resistors

It is caused by resistors connected in parallel with PMT and calculated according to the equation (4) (Spieler, 2002).

$$e_{np}^2 = 4kTR_p \frac{1}{1+(\omega R_p C_D)^2} \tag{4}$$

Where, T is absolute temperature, R_b is the parallel resistor PMT, and k is the Boltzmann constant.

2.2.5. Noise from preamplifiers

The noise of Preamplifiers was consisted of the input noise and the thermal noise of the feedback resistors. Therefore, the total noise of the preamplifiers is expressed as (5).

$$e_{nt}^2(j\omega) = e_{n1}^2\left(1+\frac{C_{in}}{C_f}\right)+\frac{1}{j\omega C_f}\left[i_n^2+\left(\frac{e_{n2}}{R_f}\right)^2\right] \tag{5}$$

Where, e_{n1} is thermal noise of first-stage FET, e_{n2} is thermal noise caused by feedback resistance, i_n is shot noise caused by the input current of preamplifier, C_{in} is the input capacitance, C_f is the feedback capacitance, R_f is the feedback resistance.

2.3. Simulate sampling signal

The sampling of signal has been done by behavioural modelling of pipeline ADC has 14-bit resolution, 500 MSPS, three stages (4+4+6). The behavioural modelling of pipeline ADC 14 bits is based on a reference from (Barra et al., 2013). After sampling, the signal was filtered so that reduce the interference by algorithm IIR filter which is given by (6).

$$y(n) = \big(y(n-2)+y(n-1)+y(n)+y(n+1)+y(n+2)\big)/5 \tag{6}$$

Where $y(n)$ is the value of sampling the amplitude at the sampling period n^{th}.

2.4. PSD algorithms

2.4.1. Rise time discrimination (RTD)

It generally measures the difference between the integrated charge in the entire pulse and the integrated charge over the rising or the falling portion of the pulse. The slope of gamma pulse tail is greater than the neutron pulse tail (time of pulse to increase from 10% to 90% of its height) (Jastaniah & Sellin, 2002).

2.4.2. Pulse gradient analysis (PGA)

PGA method using gradient analysis is applied to discriminate neutron radiation. PGA is based on the comparison of the relative heights of the samples at the tail of the pulse. It is determined by the equation (7) (Mellow et al., 2017).

$$\delta = \left|\frac{dV(t)}{dt}\right| = \left|\frac{V(k+nT)-V(k)}{nT}\right| \tag{7}$$

Where V(k) is a variable voltage level of the sampling period k^{th}, T is sampling period of the signal and n is the number of sampling periods. In approximation, if n is a constant, then $\delta \sim \left|V(k+nT)-V(k)\right|$.

2.4.3. Charge comparison method (CCM)

CCM is based on area comparison of the rising or the falling portions of the pulse. Because the gradient of neutrons and gamma pulse is different, the ratios of the area pulse, therefore, are also changed (Takaku, Oishi & Baba, 2011). The area of the pulse can be calculated by equation (8).

$$S = \int_{t_1}^{t_2} v(t)dt = \sum_{k=1}^{n} v(k).\Delta t \tag{8}$$

Where, $\Delta t = T$ is sampling period, *v(k)* is a variable voltage level of the sampling period k^{th}, t_1 and t_2 are timing of begging and ending of the sampling period, respectively.

Pattern recognition method (PRM): In this method, a signal is considered as an object vector *Y* with components are the digitized amplitude y_n of the signal at sampling time t_n. The reference vector as an object vector X was obtained by averaging over n collective gamma pulse on the same sampling system (Takaku, Oishi & Baba, 2011).

$$\overrightarrow{X} = (x_1, x_2, ..., x_n); \qquad \overrightarrow{Y} = (\mathrm{y}_1, \mathrm{y}_2, ..., \mathrm{y}_\mathrm{n}) \tag{9}$$

PRM is done by taking a scalar product of an object vector Y with the reference object vector X which describes a gamma ray or neutron signal (Takaku, Oishi & Baba, 2011).

$$r = \frac{\overrightarrow{X}.\overrightarrow{Y}}{\left|\overrightarrow{X}\right|.\left|\overrightarrow{Y}\right|} \tag{10}$$

Where, r is the correlation coefficient between vector $\vec{X}$ and vector $\vec{Y}$, $\overrightarrow{X}.\overrightarrow{Y}$ is scalar product, $|X|$ and $|Y|$ are the norm of the vectors X and Y, respectively.

$$\theta = Acr\cos\frac{\sum_{i=1}^{n} x_i . y_i}{\sqrt{\sum_{i=1}^{n} x_i^2}\sqrt{\sum_{i=1}^{n} y_i^2}} \tag{11}$$

Where, $\theta(rad)$ is the angle between the vectors, the θ value indicates the similarity of the object vector with the reference vector.

2.5. Evaluation of pulse shape discrimination methods

To evaluate the quantitative results distinguish neutron-gamma, the Figure - of - Merits (FOM) is used and defined as follows (12) (Roush, Wilson & Hornyak,1964; Bayat et al., 2012; Cerny et al., 2004; Liu et al., 2010; Takaku, Oishi & Baba, 2011; Marrone et al., 2002; Jastaniah & Sellin, 2002).

$$FOM = \frac{Ch_n - Ch_\gamma}{FWHM_n + FWHM_\gamma} \tag{12}$$

Where, Ch_n, Ch_γ are the values of neutron and gamma peaks, respectively, $FWHM_n, FWHM_\gamma$ are the full-width-half-maximum of neutron and gamma peaks, respectively, in the histogram.

3. RESULTS AND DISCUSSION

3.1. The results of simulation pulses from NE213 detector

The results of gamma and neutron pulse simulation at the same amplitude for an NE213 detector with the parameters in Table 1 is shown in Figure 3. It shows that the front of the neutron and gamma pulse is the same, while the tail pulses of gamma decreased faster than the neutron.

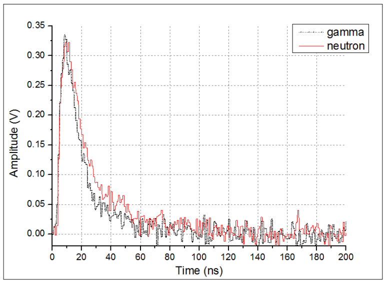

Figure 3. The pulse simulated for NE213 det

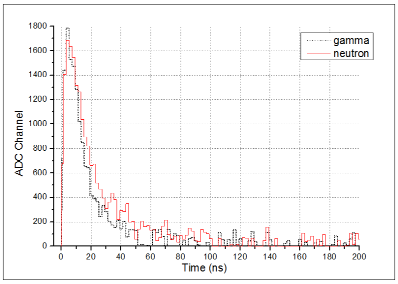

Figure 4. The pulse neutron – gamma after sampling by pipeline ADC model

3.2. Sampling the neutron - gamma pulse by pipeline ADC model

The simulation results of neutron - gamma pulse after sampling by a pipeline ADC model are resolution of 14 bits, sampling rate 500MSPS is shown in Figure 4. It shows that the pulses are added noise, but the difference in the tail pulses is still present.

3.3. The results PSD algorithms

The survey results about 100.000 pulse neutrons - gamma with algorithms: rise time discrimination, pulse gradient analysis, charge comparison and correlation pattern method, which is shown on the Figures 5, 6, 7 and 8. Figure 5 shows a scatter plot of the crossing a time threshold versus the pulse height for each waveform. Figure 6 shows a scatter plot of the calculated gradient to amplitude ratio versus the pulse height for each waveform. Figure 7 shows a scatter plot of the charge of tail to amplitude ratio versus the pulse height for each waveform. Figure 8 shows a scatter plot of the angle ratio versus the pulse height for each waveform. Figures 9, 10, 11 and 12 are the statistical charts of PSD algorithms: rise time discrimination, pulse gradient analysis, charge comparison and correlation pattern method, respectively.

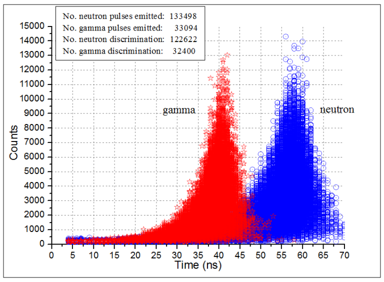

Figure 5. Time crossing the threshold versus the pulse height

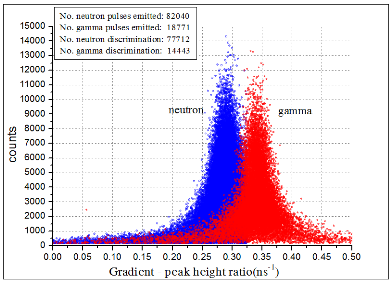

Figure 6. Gradient to amplitude ratio versus the pulse height

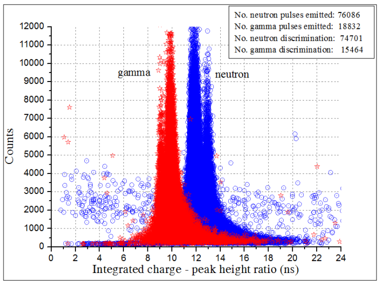

Figure 7. Charge of tail to amplitude ratio versus the pulse height

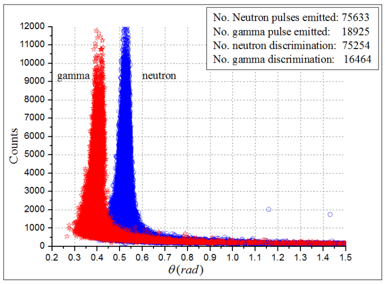

Figure 8. Angle ratio versus the pulse height

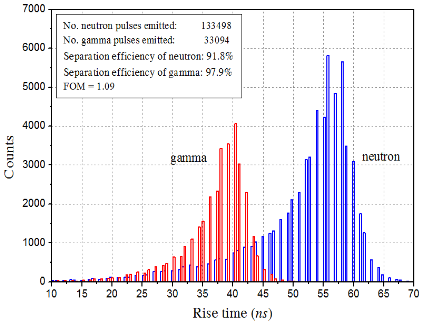

Figure 9. Rise time discrimination histogram

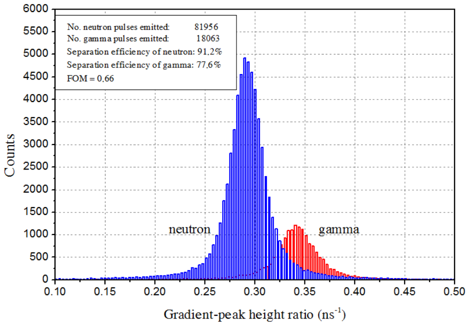

Figure 10. Pulse gradient analysis histogram

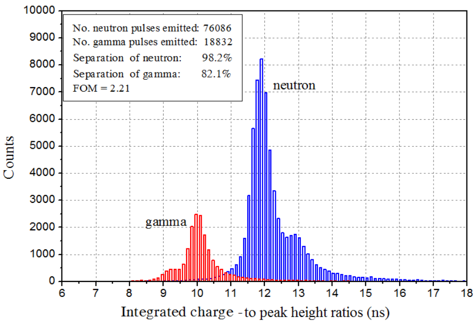

Figure 11. Charge comparison method histogram

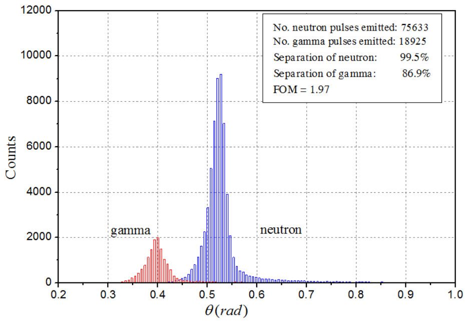

Figure 12. Correlation pattern method histogram

The FOM of these methods is shown in Table 2

Table 2. Comparing the results of the PSD methods

Methods	FOM	Neutron recognizes capacity (%)	Gamma recognizes capacity (%)	Processing time/pulse (ns)
Rise time discrimination	1.09	91.8 ± 0.3	97.9 ± 0.5	34.0 ± 4.1
Pulse gradient analysis	0.66	91.2 ± 0.3	77.6 ± 0.6	38.0 ± 4.4
Charge comparison	2.21	98.2 ± 0.3	82.1 ± 0.6	54.0 ± 5.2
Correlation pattern	1.97	99.5 ± 0.3	86.9 ± 0.6	420.0 ± 14.5

3.4. Discussion

Based on the obtained values of the FOM, recognizing capacity, and processing time, the approximately capacity of the correlation pattern method is the biggest; its processing time is too long, approximately more than eight times in comparison with others. The charge comparison has a good FOM and is fast enough to analyze pulses. It can be applied for manufacturing neutron spectrometers, which enables to measure high count rates.

4. CONCLUSION

This study simulated the signals of neutron - gamma pulses produced from the NE213 scintillator detector in Matlab and Simulink software. From the simulated pulses, the four PSD neutron-gamma algorithms have been studied with digital methods. Research results show that the FOMs of the charge comparison method and the correlation pattern method are higher than those of the rise time discrimination and pulse gradient analysis methods. In that, charge comparison method has the ability distinguishing neutron-gamma pulses well in low amplitude regions. The research results are the basis for building the neutron detection systems using NE213 scintillator detectors in combination with DSP and FPGA techniques.

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NGHIÊN CỨU CÁC THUẬT TOÁN PHÂN BIỆT DẠNG XUNG NEUTRON – GAMMA CHO DETECTOR NHẤP NHÁY

Phan Văn Chuân[a*], Nguyễn Đức Hòa[b], Nguyễn Đắc Châu[c], Vương Nữ Minh Khuê[d]

[a]Khoa Vật Lý, Trường Đại học Đà Lạt, Lâm Đồng, Việt Nam
[b]Khoa Kỹ thuật Hạt nhân, Trường Đại học Đà Lạt, Lâm Đồng, Việt Nam
[c]Học Viện Hải Quân, Khánh Hòa, Việt Nam
[d]Văn phòng Đảng ủy, Trường Đại học Đà Lạt, Lâm Đồng, Việt Nam
**Tác giả liên hệ: Email: chuanpv@dlu.edu.vn*

Lịch sử bài báo
Nhận ngày 28 tháng 09 năm 2015 | Chỉnh sửa ngày 22 tháng 10 năm 2015
Chấp nhận đăng ngày 16 tháng 03 năm 2016

Tóm tắt

Bốn thuật toán phân biệt dạng xung cho mô hình detector nhấp nháy NE213 bằng kỹ thuật xử lý tín hiệu số đã được phát triển. Trong nghiên cứu này bộ phát xung, bộ số hóa và các thuật toán phân biệt dạng xung neutron-gamma được mô phỏng trong phần mềm Simulink-Matlab. Kết quả thu được cho thấy phương thức phân biệt theo thời gian tăng có hệ số phẩm chất (Figure-of-Merits: FOM = 1,09), phương pháp phân tích độ dốc xung (FOM = 0,66), phương thức so sánh diện tích xung (FOM = 2,21) và phương thức tương quan mẫu (FOM = 1,97). Kết quả này là cơ sở để xây dựng hệ thống đo neutron sử dụng detector nhấp nháy.

Từ khóa: FOM; Mô phỏng xung nơtron và gamma; Phân biệt dạng xung nơtron-gamma; Phương thức tương quan mẫu.
